W. B. No. 203.

U. S. DEPARTMENT OF AGRICULTURE,

WEATHER BUREAU.

VARIATIONS IN LAKE LEVELS

AND

ATMOSPHERIC PRECIPITATION.

Prepared under direction of WILLIS L. MOORE, Chief U. S. Weather Bureau.

BY

ALFRED J. HENRY,
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VARIATIONS IN LAKE LEVELS AND ATMOSPHERIC PRECIPITATION.*

The attempt to correlate data of precipitation and oscillations in lake level was begun on the June issue of the Meteorological Chart of the Great Lakes, on which, it will be remembered, records of the monthly amounts of rain and melted snow at nearly 300 stations in the watershed of the Great Lakes were published. The period covered by the records was from November, 1898, to April, 1899. It is intended to publish on future issues similar data for the remaining six months of the rain year, and to prepare a chart showing the average precipitation in inches over the entire watershed for the current season.

What indication such a chart will afford of the stage of water during the coming winter and spring is at present wholly problematical. Meanwhile, we have an opportunity of determining in a crude manner, it is true, whether the records of past years show any definite relation between the yearly precipitation on the one hand and the average level of the lakes on the other.

It is understood, of course, that the level of a lake is not wholly dependent upon the precipitation that occurs within its watershed. The quantity of water that flows into the lake, which for convenience may be called the runoff, is more or less variable, depending upon the character of the soil, the intensity of rainfall, and the attendant weather conditions. On the lower peninsula of Michigan the runoff has been estimated to be as much as 50 per cent of the total rainfall. Over the forested areas of the upper portion of the peninsula it is undoubtedly much less. Runoff increases as a result of deforestation, hence we should expect the runoff of to-day to be greater than it was thirty years ago. The effect of increased runoff, resulting from deforestation in the Lake region during the last half century, would be felt in an ordinary river system, but is probably inappreciable on the Great Lakes. The sudden melting of the winter snow greatly increases the runoff and materially increases the natural supply of the lake, while on the other hand, a gradual thawing and prolonged cold weather permits a large quantity of water to escape into the air by evaporation, the evaporation from snow and ice being almost equal to that from a water surface under similar conditions as to temperature, wind velocity, and dryness.

After prolonged drought, and generally in years of deficient precipitation, the runoff, corresponding to a given quantity of rain, is much less than during times of normal or excessive rainfall. We should not expect, therefore, to find at all times a very rigid connection between the amount of rain and snow that falls and the level of the lake during the corresponding period.

The important variations in the surface level of the Great Lakes may be conveniently divided into two classes, viz, periodic and nonperiodic.

The periodic or annual variation is a comparatively simple phenomenon, viz, the rise in level of the water of the lakes from a minimum in winter to a maximum in summer, and depends largely, if not altogether, upon the precipitation of rain and snow in the watershed of the Great Lakes.

Superposed upon the annual variations and apparently entirely independent of them, is another set of oscillations differing from the first-named both in the amplitude of the oscillations and the length of time required in passing from a period of low to a period of high water, or vice versa. The amplitude of any single nonperiodic variation differs widely from that of another, as also the time usually occupied in passing from one maximum stage to the next.

Annual variation.—The annual variation of surface levels for Lakes Superior, Michigan, and Huron, as determined by the United States Deep Waterways Commission, is graphically shown by Diagram I. The latter is based on observations of water level made under the direction of officers of the Engineer Corps, United States Army, and published both in the Annual Reports of the Chief of Engineers and the Report of the United States Deep Waterways Commission, 1896. Numerical values are given below.

* Reprinted from Meteorological Chart of the Great Lakes, 1899.

Table I.—*Normal monthly mean for thirty-six years of water levels below the plane of reference of United States Lake Survey (high water of* 1838), *in feet.*

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Mean.
Lake Superior[1]...	3.37	3.54	3.60	3.51	3.20	2.95	2.75	2.65	2.61	2.66	2.85	3.15	3.07
Lake Michigan[2]...	3.53	3.50	3.34	3.13	2.87	2.63	2.57	2.63	2.83	3.06	3.32	3.55	3.08
Lake Huron[2]......	3.46	3.50	3.41	3.25	2.93	2.68	2.55	2.61	2.79	3.01	3.23	3.45	3.07

[1] Elevation of the plane of reference above mean tide at New York City is 604.76 feet.
[2] Elevation of the plane of reference above mean tide at New York City is 584.34 feet.

Table II.—*Average monthly distribution of precipitation in the watersheds of the Great Lakes, in inches.*

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
Lake Superior	1.5	1.3	1.5	2.2	2.9	3.4	3.2	2.9	3.8	2.9	2.6	1.7
Lake Michigan.....................	2.1	2.0	2.3	2.6	3.4	3.7	3.1	2.8	3.1	2.6	2.5	2.2
Lake Huron	2.7	2.3	2.4	2.0	3.2	3.0	2.7	2.7	3.5	3.6	3.4	3.3

The distribution of precipitation throughout the year is graphically shown by the curves of Diagram II, and the numerical values are given in Table II. The reader is cautioned against summing the monthly averages for the several lakes, and using the result as the annual precipitation values of the several drainage basins. The latter, as computed from a greater number of stations, is given below.

	Inches.
Lake Superior	28
Lake Michigan...	33
Lake Huron..	32
Lake St. Clair	35
Lake Erie...	36
Lake Ontario..	33

The general similarity in the two sets of curves representing, respectively, the seasonal rise and fall of lake levels and the amount and distribution of precipitation, is seen at a glance.

The curves of mean annual variation of water levels differ among themselves mainly in the time of maximum and minimum phases; thus, for Superior the lowest water occurs in March, while for Michigan it occurs in December, and for Huron in February. The highest water on Superior occurs on the average in September; on Michigan and Huron in July. The lowest water on Superior occurs near the end of winter, when adjacent land areas are contributing very little water to the lake. The lowest water on Lake Michigan occurs in December, although the low water period extends well through the winter months. The period of annual low water on Lake Huron falls in February.

The precipitation curves, Diagram II, for the three lakes under consideration are alike in general form, but possess important minor differences. A feature common to all of them is an early maximum of rain in May or June, followed by lighter rains in midsummer, and a second maximum in September. In the case of Superior the September rains are the heaviest, and we note that the time of highest water on that lake also falls in September, although the high water does not necessarily follow as a direct result of September rains. These remarks apply to average conditions only. The time of highest water on Superior may, and often does, fall in August, while the spring and early summer rains may be much heavier at times than those of September. The chief maximum, or time of heaviest rains on the average on Lake Michigan, falls in May and June, and there is a lesser maximum in September, while the time of highest water falls in July. The chief maximum on Lake Huron occurs in September and October,

the secondary or lesser maximum occurring in May and June. The period of high water on Lakes Michigan and Huron does not occur coincidently with the time of greatest rain, but about a month afterwards, or at a time when we may suppose the inflow from all sources has reached a maximum.

The precipitation of the Superior basin is largely in the form of rain, notwithstanding the heavy snows that fall on the southern shore. The winter fall of snow on the Canadian side is much less than that of the American side. The annual rise in the lake generally begins with the melting of the winter snow early in April, and continues steadily until the crest is reached in August or September. In warm, open winters the rise may begin in February or March, but in such cases it is quite probable that it will not continue steadily until the summer maximum is reached. Thus, during the very warm winter of 1877–78 the water began to rise in January, and continued to rise during February; it fell during March and April, however, reaching the lowest point of the year in the latter month. It would seem that the amount of snowfall during the winter has an important bearing upon the level of the lake during the following summer.

The Lake Michigan basin being farther south and nearer the path of storms advancing from the southwest, receives a heavier winter precipitation than Superior, and this is also true of Huron, which receives a greater winter precipitation than either Michigan or Superior. The precipitation of the late fall months in the Huron basin is also considerably greater than in the remaining basins. On the whole, precipitation in the Huron basin is more evenly distributed throughout the year than in the case of Lakes Michigan and Superior.

The two lakes, Huron and Michigan, are generally considered as a single system so far as the level of the water in them is concerned. We have elsewhere noted that the lowest water on the average in Lake Michigan occurs in December and January, and in Lake Huron in February. The precipitation in the Michigan basin decreases steadily from September to midwinter. If the level of the lake depended solely upon the precipitation on its watershed we should expect better agreement between the periods of least precipitation and low water, respectively. Instead of low water occurring in December we should expect it to occur in February, as on Lake Huron.

The month of least precipitation on the average in the Huron basin is April, while the lowest water of the year occurs in February.

Precipitation shades off from December to January rather abruptly, and there is a further diminution from January to February.

The time of least precipitation in the several basins appears to be so adjusted by nature as to cause the least lowering effect on the surface of the lakes. In the Superior basin and the northern part of the Michigan basin, while the least precipitation of the year occurs in midwinter, it is generally conserved by the forested areas, and we are of opinion that a relatively large portion of it finds its way into the lakes on the approach of warm weather. As we go southward on the chain of lakes we find in the Huron basin that the least precipitation of the year occurs in February, March and April, somewhat later than in the Michigan and Superior basins. It is therefore reasonable to suppose that the level of Lake Michigan should begin to rise sooner than Huron, and this is found to be the case. It has been suggested in further explanation of the fact that the times of average low water and least precipitation on Lake Huron are not coincident, that the heavy ice in the Straits of Mackinac tends to reduce the flow from Lake Michigan, such effect being at a maximum in February.

Nonperiodic variations.—In this preliminary attempt to study the phenomena of precipitation and nonperiodic fluctuations in lake levels it has been necessary to select Lake Michigan, although the problem would have been simplified somewhat had it been possible to have chosen Lake Superior. Unfortunately, there are no records of precipitation on the Canadian side of the latter, prior to 1878, and for that matter very few on the American side. In the case of Lake Michigan it was necessary to use a few rainfall measurements made outside of the watershed in order to get a fairly accurate idea of the variations of rainfall year by year.

At the outset the reservation is made that absolute dependence can not be placed upon the rainfall curve for the period 1860–1870. After that time it is believed the actual rainfall conditions are fairly well represented by the curve. A word as to how the curves were made.

The water level curve is based upon observations of lake level made at Milwaukee, Wis., by officials of the Engineer Corps of the army, the mean annual values being smoothed by the well known formula $\frac{a+2b+c}{4}$ where b is the

middle year and a and c the years immediately preceding and following. The actual smoothed values both of water levels and departures from normal precipitation are given in Table III.

The lower curve of Diagram III shows the average departure from the normal precipitation for the whole basin, in inches, plus values being above and minus below the normal. In computing the yearly departure from the normal no station was used that did not have a record of at least twenty years. This limitation considerably reduced the number of available stations. Thus, for 1860 only four were available, viz: Milwaukee, Thunder Bay Island, Chicago, and Detroit. By 1871 five additional stations had become available, and this number was maintained thereafter.

The ordinates of the rainfall curve represent inches and tenths of inches above or below the normal.

TABLE III.—*Average annual level of Lake Michigan and precipitation departures in its watershed for each year from* 1860 *to* 1898.

(Plus values are above and minus below normal in inches and tenths.)

Lake levels.			Precipitation departures.		Lake levels.			Precipitation departures.	
Year.	Actual.	Smoothed.	Actual.	Smoothed.	Year.	Actual.	Smoothed.	Actual.	Smoothed.
	Feet.	*Feet.*	*Inches.*	*Inches.*		*Feet.*	*Feet.*	*Inches.*	*Inches.*
1860	2.01	2.02	—5.0	—2.1	1880	3.40	3.30	+6.7	+5.2
1861	2.03	2.03	+3.7	—0.7	1881	2.88	2.92	+8.3	+6.8
1862	2.07	2.18	—5.2	—2.4	1882	2.51	2.56	+3.8	+5.2
1863	2.54	2.58	—2.7	—3.9	1883	2.36	2.37	+5.1	+4.5
1864	3.16	3.06	—5.1	—4.0	1884	2.26	2.22	+3.9	+3.8
1865	3.40	3.42	—3.0	—2.7	1885	2.01	2.01	+2.2	+1.8
1866	3.73	3.54	+0.4	—2.7	1886	1.77	1.99	—1.1	—0.4
1867	3.29	3.52	—8.7	—4.4	1887	2.41	2.40	—1.6	—2.2
1868	3.78	3.63	—0.8	—1.8	1888	3.02	3.00	—4.6	—4.2
1869	3.66	3.46	+3.0	+0.4	1889	3.57	3.46	—6.0	—4.0
1870	2.75	3.00	—3.7	—2.0	1890	3.68	3.79	+0.7	—2.0
1871	2.82	3.12	—3.8	—4.7	1891	4.24	4.13	—3.2	—0.8
1872	4.10	3.62	—7.6	—5.2	1892	4.35	4.25	+2.6	+0.8
1873	3.45	3.49	—1.6	—4.2	1893	4.07	4.11	+1.2	+0.1
1874	2.96	3.14	—6.0	—3.6	1894	3.95	4.24	—4.7	—4.0
1875	3.21	2.86	—0.6	—0.5	1895	4.99	4.80	—7.7	—5.6
1876	2.08	2.42	+5.1	+2.8	1896	5.26	5.04	—2.2	—3.5
1877	2.31	2.33	+1.6	+2.9	1897	4.63	4.75	—1.8	—1.4
1878	2.62	2.77	+3.4	+1.9	1898	4.43	4.40	+0.3	—0.4
1879	3.51	3.28	—0.8	+2.1					

Passing now to the consideration of the two curves of Diagram III, representing, respectively, the fluctuation in the level of Lake Michigan and of the yearly precipitation in the watershed of that lake, we may remark that there are certain points of resemblance, but not such a connected and consistent relation between the two conditions as we had hoped to find. At the beginning of the record in 1860, a year of markedly deficient rainfall, in the Lake Michigan basin at least, the lake was almost as high as at any subsequent time in the forty years which have since elapsed. The high water may be accounted for on the ground that heavy rains may have fallen in the years immediately preceding. The rainfall of the two years previous at the only station in the Lake Superior basin at which measurements were made, was excessive. From the few weather records made in the basin of Lake Michigan it may be inferred that 1859 was nearly a normal year as regards rainfall, and that 1858 was a very wet year. On the whole the available records of rainfall are not conclusive on this point.

The course of the nonperiodic fluctuation during the years 1862–1865 was downward, the fall being slightly checked in 1866–67 by an increase in precipitation. From 1868 to 1870 the lake level rose, apparently responding to the heavy rains in portions of the Lake region in 1869. From 1870 to 1872 the rainfall was considerably less than normal, and the effect is shown in the downward course of the lake level curve. A period of increased rainfall began in 1872, continuing until the end of 1876. The lake level rose in apparent response to the increasing rainfall, the crest of high water and the time of greatest rainfall occurring almost coincidently in the summer of 1876. From 1877 to 1879 the three upper

lakes steadily fell, the fall being well marked on all of them. Low water of the winter of 1876–77 on Lake Superior was not reached until April, 1877. The fall in the level of that lake from low water of 1876 to low water of 1879 was over a foot. The rainfall at the beginning of the period in the Superior basin was more or less deficient, yet for the three years, at a majority of the stations, it was slightly above normal, although less than that of 1876. The depression of over a foot in the general level of Lake Superior, a lake presumably not affected by conditions which may exist outside of its own watershed, is not easily explained. It is true a fall from the high water of 1876 was to be expected, yet we should hardly expect a fall so disproportionate to the actual diminution in rainfall.

The unknown causes which might have contributed in a measure to the depression are (*a*), very great evaporation from the lake itself; (*b*), an unusual outflow or discharge; and (*c*) the effect of temporary winds in changing the level of the water.

We do not know whether causes (*b*) and (*c*) contributed to the fall in the level of the lake or not. As a matter of personal opinion we should say very little if any. The effect of cause (*a*) might have been considerable as we shall attempt to show.

The amount of evaporation that takes place from the surface of a body of water depends chiefly upon the dryness of the air, the wind velocity, the temperature of the evaporating water, and the superincumbent air. Lake Superior, by reason of its abnormally cold water and the relatively cool stratum of air immediately above it, possesses less energy of evaporation than the remaining lakes.

The energy required in evaporation comes originally from the sun; the stronger the heat rays and the higher the temperature of both air and water the greater the evaporation. The thermal conditions of the air over Lake Superior, as of other regions in the middle of the continent, are subject to considerable variations from year to year. For 1877 the annual mean temperature at Marquette, Mich., was 3.9° above the average of twenty-four years; for 1878, 6.0° above the average, and this was the warmest year since Weather Bureau observations began; for 1879 it was 2° above the average. The temperature of the lake water, as observed at Duluth and Marquette, was also much higher than usual, especially during 1878. These conditions, coupled with periods of greater or less dryness, would naturally greatly increase evaporation from the lake surface.

Unfortunately we have no direct measure of the amount of water evaporated from the lake during the years in question, but we can arrive at approximate results indirectly.

In the summer of 1888 observations of evaporation by Piché evaporometers were made in the Lake region and elsewhere in the United States. These observations were discussed by Prof. Thomas Russell in the September, 1888, Monthly Weather Review, wherein he deduces a formula for the computation of the possibilities of evaporation from the readings of the wet-bulb thermometer and other observed data as follows:

$$E = 30\left(\frac{A\,p_w + B\,(p_w - p_d)}{b}\right) \text{ where}$$

$E =$ Evaporation in inches; A and B are constants (1.96 and 43.9, respectively); p_w the vapor pressure corresponding to the monthly mean of the wet bulb thermometer; p_d the vapor pressure corresponding to the temperature of the dew-point, and b the local pressure at the place of observation. The possibilities of evaporation for 1878, and also for the twelve months, June, 1887–July, 1888, computed by the above formula, are shown in Table IV.

TABLE IV.—*Possibilities of evaporation at Marquette, Mich.*

Year.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
1878	1.3	2.1	2.5	2.6	3.2	3.8	5.2	4.7	3.5	2.7	2.0	1.1	34.7
1887–88	0.8	0.8	0.9	1.7	2.4	3.3	3.4	3.3	3.1	2.2	1.3	1.3	24.5

We thus see that during the warm, dry year, 1878, the atmospheric conditions were such that it was possible for 34.7 inches of water to have evaporated from the lake, being a little over 10 inches above the amount that was possible dur-

ing the twelve months, July, 1887–June, 1888, and about 2 inches more than the normal annual precipitation. As the conditions which existed on Lake Superior in 1878, doubtless extended over the greater part of the upper lake region, we may safely assume that evaporation played an important part in producing the low water of 1877–1879.

We have not computed the possibilities of evaporation for 1877 and 1879, the results given in the above table being sufficient for our purpose.

The low water of 1877–1879 was followed by a period of high water, the level of the lakes rising steadily from 1880 to 1886, when the high-water mark of the forty years was reached. The increased volume of water was undoubtedly a direct result of the abundant rains of 1880–1885. The rainfall of the years 1881 and 1883 was especially heavy, although there was not a correspondingly marked increase in the level of the lake. The latter rose gradually to a maximum stage in 1886, several years after the years of maximum rainfall. On the other hand it should be observed that the rainfall of 1884 and 1885 was above normal and that a marked diminution in fall did not occur until 1886. The effect of the heavy precipitation seems to have been cumulative, that is to say, the level of the lake rose each year, except 1884, a little higher than it had been during the previous year, the increase in level thus gained being maintained by the abundant rainfall. It is obvious that a single year of heavy rains followed by a year of less than the normal amount of rain can have but a transient effect on the general level of the lakes. If, however, a single year of heavy rain be followed by another of the same character, or even by a year of normal rain, there should be a perceptible increase in the level of the lakes.

Beginning in 1887 the level of Lake Michigan began to fall and continued falling until 1893. The precipitation began to diminish in 1886, and was below normal in 1887, 1888, and 1889, the average deficiency in the watershed during the last-named year being 6 inches. The precipitation of the following year, 1890, was almost an inch above normal, yet the level of the lake continued to fall, and it was not until two years of more than normal rainfall occurred, 1892 and 1893, that the downward course of the lake level was checked. It should be noted that during an earlier period, 1870 to 1875, there was a greater deficiency of precipitation than occurred in 1886–1889, yet the lake did not fall to so low a stage as in the last-named period. The level of the lake continued to fall after the slight check in 1893, the rainfall of 1894, 1895, and 1896 being deficient. The lowest stage of the forty years was reached in 1896. That the level of the lake should fall was to be expected, but that it should remain so far below the normal stage in spite of the fact that the rainfall of both its own watershed and that of Lake Superior was not far from average seems inexplicable, unless we look elsewhere for the underlying causes.

At this point in the investigation the attention of the writer was called to the fact that in 1885 and 1886 the slope between Lake Huron and Lake Erie was greater than at any other time covered by the records, and that immediately following this period the difference in levels between the two lakes began to diminish. Mr. George Y. Wisner, member of the Board on Deep Waterways, who communicates the information, expresses the opinion that it seems probable that the excessive slopes existing in 1885-1886 were the initial causes which led to the increase in cross section recently found at the head of the St. Clair River. The further opinion is expressed that the levels of Lake Huron, Lake Michigan, and Lake Erie have to a certain extent been affected by the deepening of connecting waterways and outlets. This, together with the increase in cross section at the head of St. Clair River, has apparently permanently lowered the level of Lake Huron and Lake Michigan something over a foot, and incidentally St. Marys River below the rapids a similar amount.

These conclusions appear to be confirmed by the rainfall records.

Summarizing the foregoing we may remark that it seems possible to indicate the level of the Lakes, approximately at least, by closely observing the precipitation in the various watersheds, especially the amount of snow and the manner of its disappearance. All inferences as to the probable effect of precipitation on Lake levels must be contingent, however, upon the maintenance of a constant cross section and slope in the present connecting channels.

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Diagram I. Mean Annual Variation—Lake Superior.

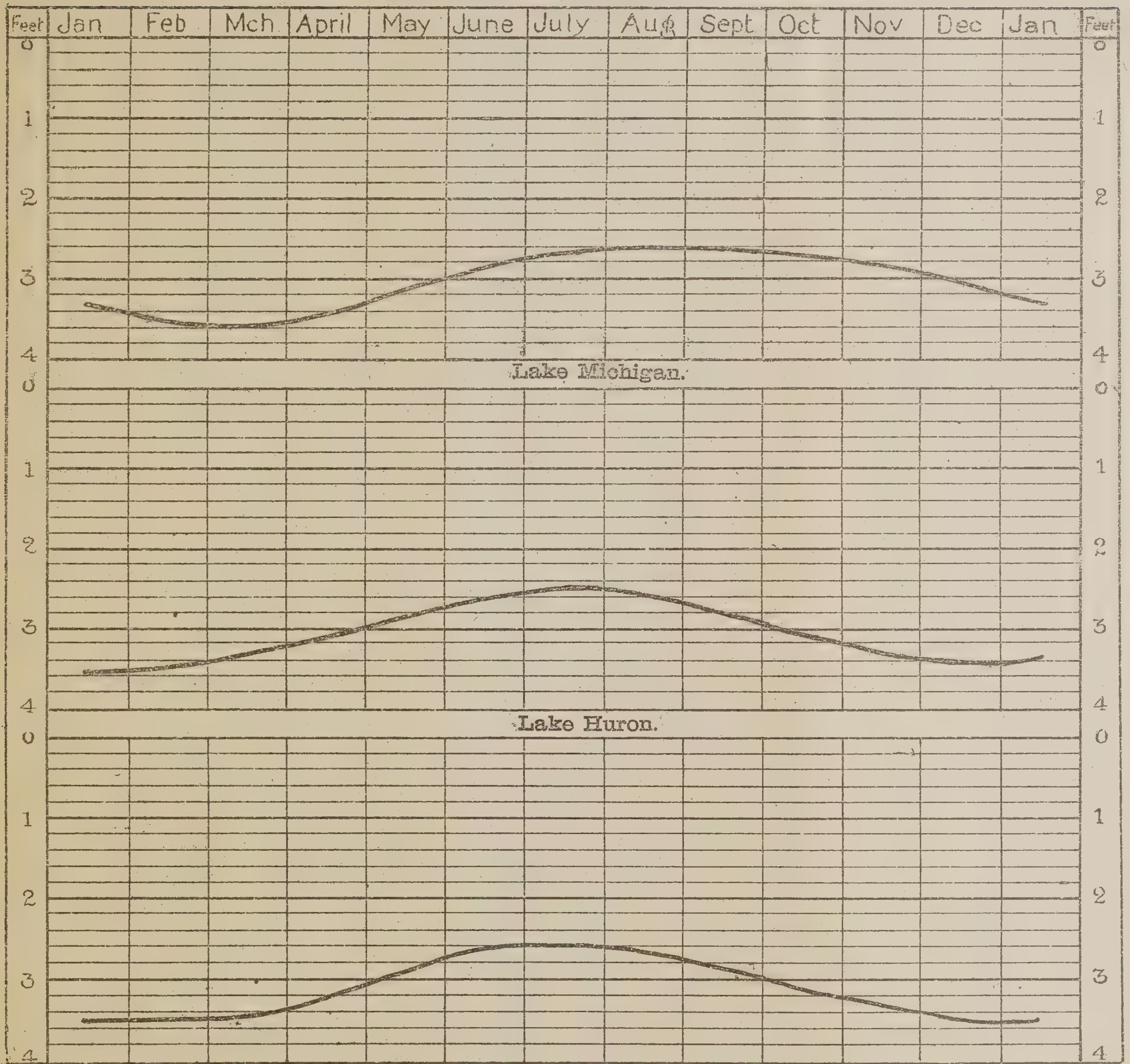


Diagram II. Monthly Distribution of Precipitation—Lake Superior.

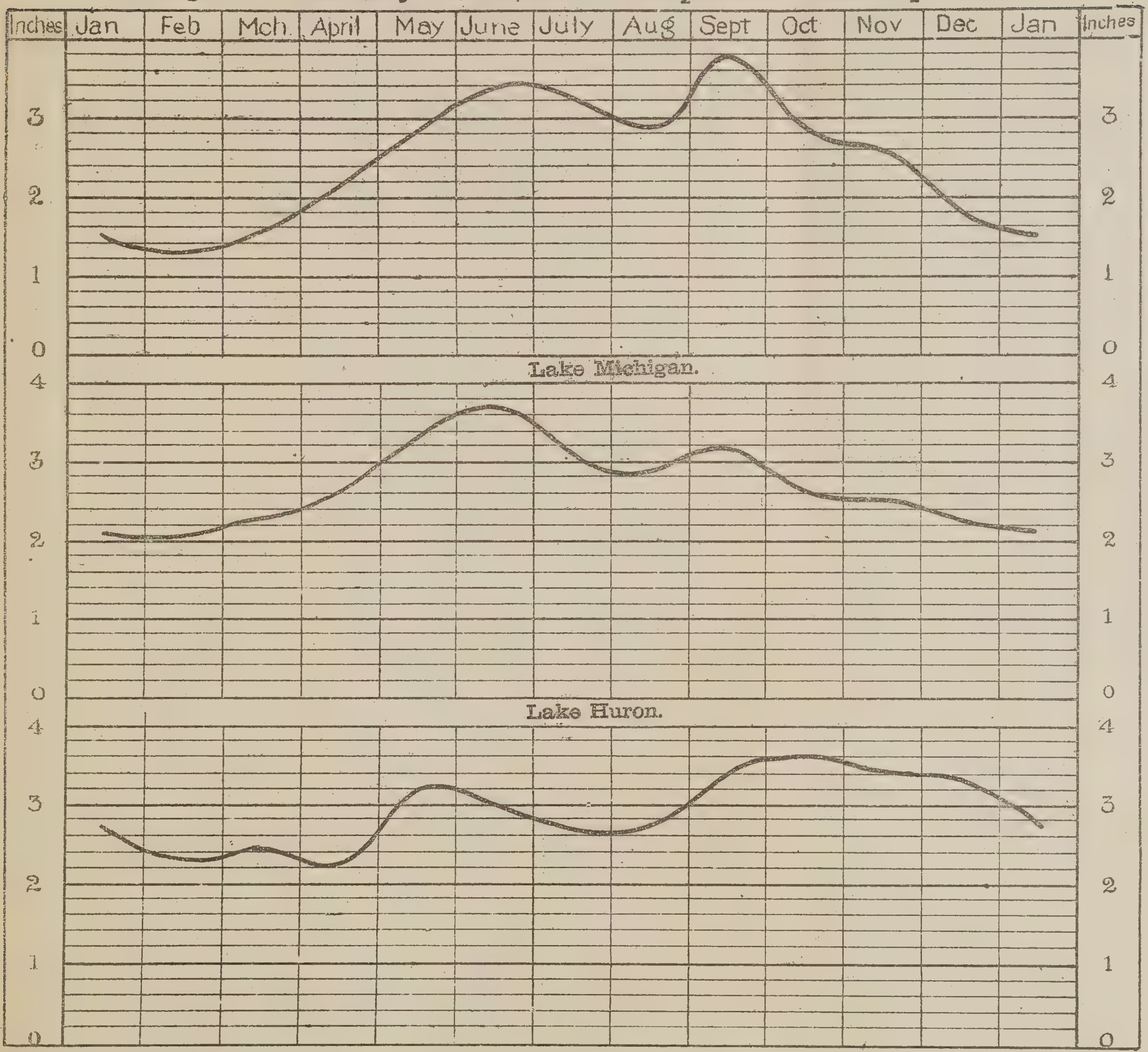
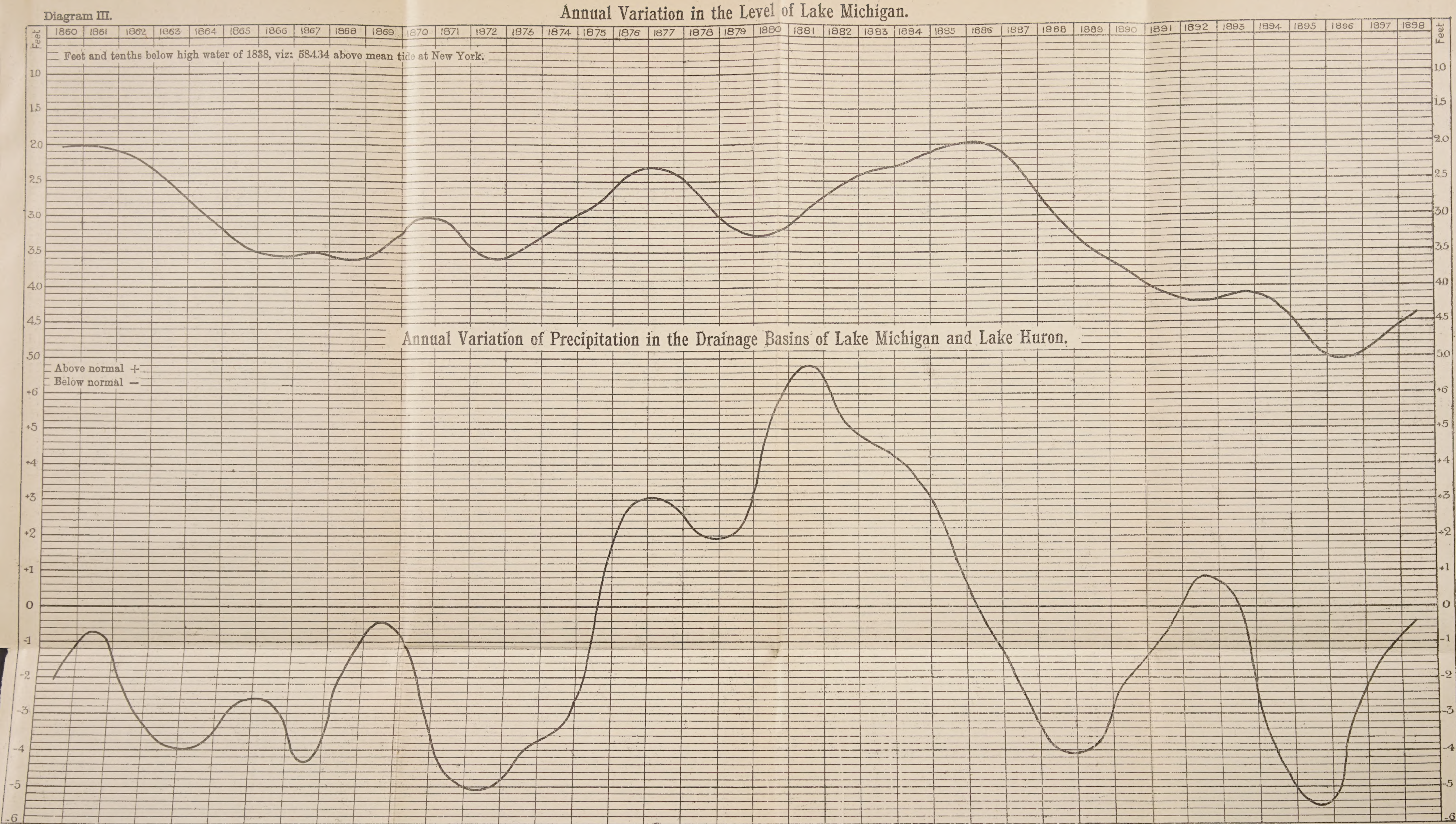


Diagram III.


Annual Variation in the Level of Lake Michigan.
Feet
1860 1861 1862 1863 1864 1865 1866 1867 1868 1869 1870 1871 1872 1873 1874 1875 1876 1877 1878 1879 1880 1881 1882 1883 1884 1885 1886 1887 1888 1889 1890 1891 1892 1893 1894 1895 1896 1897 1898
Feet and tenths below high water of 1838, viz: 584.34 above mean tide at New York.
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Annual Variation of Precipitation in the Drainage Basins of Lake Michigan and Lake Huron.
Above normal +
Below normal −
+6 +5 +4 +3 +2 +1 0 -1 -2 -3 -4 -5 -6